Design and Operation of Burn-In Test System for Three-Phase Uninterruptible Power Supplies

Shyh-Jier Huang, *Senior Member, IEEE*, and Fu-Sheng Pai

***Abstract*—In this paper, a new approach for the burn-in test of three-phase uninterruptible power supplies is proposed. This method can perform the energy recovery for reducing the test cost, while the current supplied from the utility can be steered to be more sinusoidal. When a large number of burn-in test systems are activated such that harmonic problems may become more serious, the proposed method is also suggested based on its immunity to possible harmonics infiltration coming from the tested product to the utility power supplies. This method has been tested through simulation study and hardware experiments. Test results help consolidate the feasibility of the approach for the applications considered.**

***Index Terms*—Burn-in test, uninterruptible power supply.**

I. Introduction

As UNINTERRUPTIBLE power supplies (UPSs) can serve as reliable electric power sources, they currently are widely used at the customer side to mitigate the problems of power quality deterioration. However, before the employment of the UPS for power quality improvement, its operation reliability is a vital concern that needs to be qualified in a prudent manner [1]–[3]. The burn-in test is recognized as a feasible approach for quality certification of a new UPS product, yet with the resistor bank used for the virtual testing load, it often results in unwanted energy consumption that inadvertently causes the cost increase of the final product. Therefore, an energy-saving method for this burn-in test is deemed crucial to both utility and industry.

Recently, the power recycling method for a UPS burn-in test has been addressed in the literature [4], [5]. This method utilized a regulating transformer and inductor as an interface between the tested UPS and utility grid, where the amplitude and phase of the transformer can be properly controlled. Most of the required power for the burn-in test is also recovered to the utility grid for the compensation instead of dissipation. However, one inconvenience found in this method is the usage of passive and heavy equipment for the bulk volume consideration. To overcome the drawback, some voltage-controlled inverters were, hence, suggested in the replacement of those passive elements [3]; yet since both amplitude and phase angle of the inverter output voltage must be carefully controlled, the circuit design may become more complicated. The current-controlled inverters were also investigated for the burn-in test applications, which were reported to exhibit the good ability of creating the recycling current with high power factor for the test needs [4]–[6]. Nevertheless, one problem lies in the possibility that the input harmonic current of the tested UPS may infiltrate the supplying power. In particular, when large numbers of this type of UPS are simultaneously scheduled for the burn-in test, harmonic problems will unavoidably become serious. Several UPS manufacturers have implemented the harmonic filter in their products; however, in view of cost competition, the number of the rectifier type of UPS without filter implemented is still at a sufficiently high percentage of total three-phase UPS sales (about 50% in Taiwan). Hence, the quality of supplying power is a critical issue, thereby motivating the improvement of the burn-in test method proposed in this paper.

In the paper, a new method for a three-phase UPS burn-in test is proposed. A current-controlled inverter is suggested for the achievement of both energy recovery and harmonic compensation and the controller is designed for the appropriate control of the circulating current in which the utility current is also maintained to be more sinusoidal. Some useful features of this method are listed as follows.

1) It provides effective power recycling ability that helps curtail the amount of energy waste.
2) The inverter in the proposed system supplies the active power and compensates harmonic power simultaneously. The degree of harmonic pollution to the ac sources can be better restricted.
3) The circuit in the test system is relatively easy to accomplish. Development and implementation costs can both be reduced.

This paper is organized as follows. Section II presents the system description, Section III discusses the control method, Section IV describes the design considerations, Section V demonstrates the simulation test and experimental results, and Section VI draws conclusions.

II. Description of the Proposed System

A. Burn-In Test System

Fig. 1 shows the block diagram of a burn-in test system [3]–[6]. In the figure, the tested UPS is connected to the utility ac source, where the subsequent burn-in test system is used as a virtual load. As the figure depicts, because the UPS is connected in series with the burn-in test system, its output power will be propagated throughout the test system and then injected into the utility grid. The relationships between tested

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The authors are with the Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan 70101, R.O.C. (e-mail:clhuang@mail.ncku.edu.tw).

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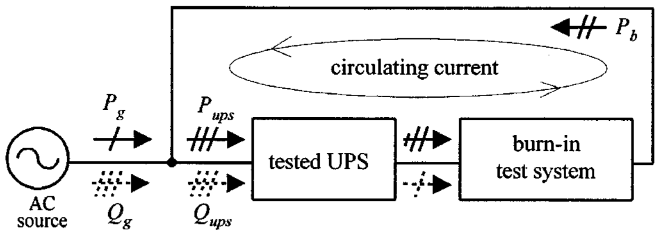

Fig. 1. Conventional UPS burn-in test system.

system output real power P_b and UPS input fundamental real power $\bar{p}_{\mathrm{ups}}$ can be formulated as follows:

$$P_b = \eta \times \bar{p}_{\mathrm{ups}} \tag{1}$$

where η is the operational efficiency. However, due to ac-to-dc conversion at the input stage of UPS, the input power of the UPS $(P_{\mathrm{ups}}, Q_{\mathrm{ups}})$ is known to be not only composed of fundamental components, but also of different orders of harmonics, which can be written as follows:

$$\begin{aligned} P_{\mathrm{ups}} &= \bar{p}_{\mathrm{ups}} + \tilde{p}_{\mathrm{ups}} \\ Q_{\mathrm{ups}} &= \bar{q}_{\mathrm{ups}} + \tilde{q}_{\mathrm{ups}} \end{aligned} \tag{2}$$

where p_{ups} and q_{ups} are components corresponding to the fundamental real and reactive power and $\tilde{p}_{\mathrm{ups}}$ and $\tilde{q}_{\mathrm{ups}}$ are harmonic power. By using (1) and (2), the power supplied from the utility source (P_g, Q_g) can be rewritten as follows:

$$\begin{aligned} P_g &= (1-\eta)\bar{p}_{\mathrm{ups}} + \tilde{p}_{\mathrm{ups}} \\ Q_g &= \bar{q}_{\mathrm{ups}} + \tilde{q}_{\mathrm{ups}}. \end{aligned} \tag{3}$$

As (3) discloses, the needed power from the grid includes those undesired harmonics and reactive component. In other words, if such a tested system is employed, the power factor and power quality at the test side will be degraded, thereby increasing the possibility of damaging the sensitive equipment because of harmonic pollution. This also informs us that a tested system with low harmonic pollution would be attractive from the perspectives of both utility and UPS manufacturers.

B. Proposed System

Fig. 2 shows the main circuit of the proposed burn-in test system. In the figure, the system is composed of a step-up transformer with the leakage inductance, bridge rectifier, dc capacitor, and grid-connected inverter. When the tested UPS is active, the rectified current is drained from the UPS and then charged to the dc capacitor through the transformer and rectifier. Therefore, the dc voltage is established across the capacitor at which the energy drained from the UPS is temporarily stored. Following this, a grid-connected inverter is added for the energy regeneration, where a current-controlled controller is adopted to yield the gated switching signals. In this figure, current transformers (CTs) are also seen installed at the ac source side for sampling the current supplied from the utility source which is named the *utility current* in this paper. With the activation of the

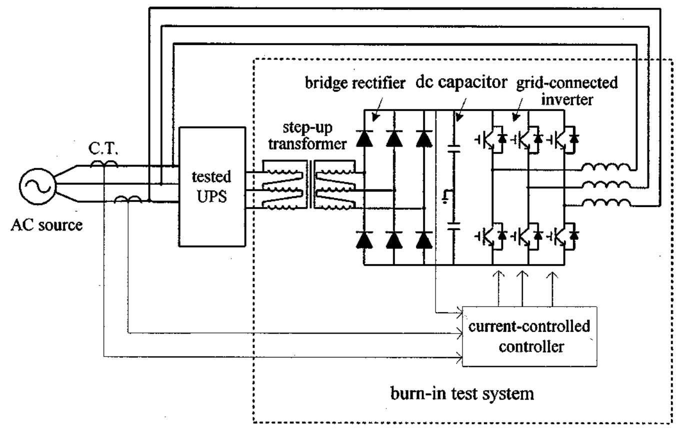

Fig. 2. Proposed burn-in test system.

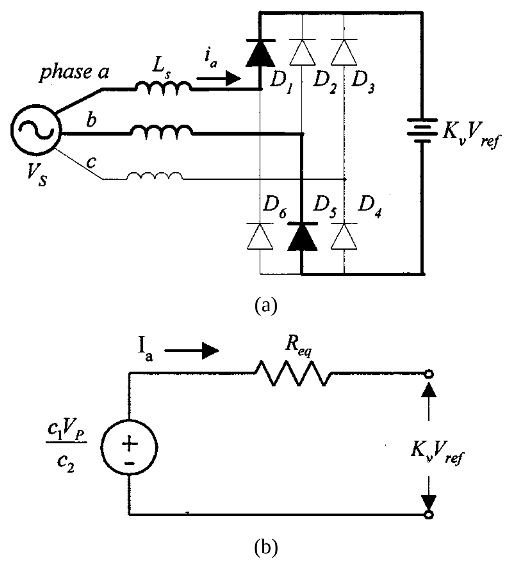

Fig. 3. Circuit model representing the circulating testing current control in the proposed system. (a) Circulating current flow. (b) Equivalent circuit.

inverter, the temporary energy stored at the dc capacitor will be released and returned to the UPS input; therefore, a circulating current flowing around the overall system is formed. However, because of the operational loss, a relatively small power is additionally required, supplied from the utility source. To satisfy this requirement while reducing the degree of harmonic distortions, the inverter in the proposed circuit is thus designed to supply the compensation current that can also steer the utility current toward sinusoidal. In this way, the required amount of compensation current for UPS input is no longer fully supplied from the grid, thereby reaching a better way of energy saving.

III. Control Method

A. Circulating Current Control

Fig. 3(a) shows the equivalent circuit, where the tested UPS and step-up transformer are the supplying power represented by the voltage source V_s connected in series with the inductance L_s. In the figure, the equivalent voltage source $K_v V_{\mathrm{ref}}$ is seen from the dc capacitor to inverter output, where V_{ref} is the voltage reference preset at the controller and K_v is the voltage gain between the dc capacitor voltage and the feedback voltage signal of the controller. In this circuit, two diodes are always seen conducted in series at any given time if the commutation process of the diode is neglected [7]. Fig. 3(a) describes a scenario when D_1 and D_5 are paired conducted, in which the current i_a on the ac side of the rectifier can be derived as follows:

$$2L_s \frac{di_a}{dt} = V_p \sin\theta - K_v V_{\text{ref}} \tag{4}$$

where V_p is the crest value of the line–line voltage. Let $\theta = \omega t$, then, the following equation can be derived:

$$di_a = \frac{1}{2\omega L_s} \left(V_p \sin\theta - K_v V_{\text{ref}}\right) d\theta. \tag{5}$$

By carrying out the integration of (5), it becomes

$$i_a(\theta) = \frac{-1}{2\omega L_s} \left(V_p \cos\theta + K_v V_{\text{ref}} \theta\right) + C \tag{6}$$

where C is the integration constant. At this time, if this diode pair is assumed to begin being conducted at θ_s and ends at θ_f, boundary conditions can be described as follows:

$$\begin{cases} i_a(\theta_s) = 0 \\ \theta_f = \theta_s + \frac{\pi}{3}. \end{cases} \tag{7}$$

By substituting (7) into (6), (8) can be obtained

$$C = \frac{1}{2\omega L_s} \left(V_p \cos\theta_s + K_v V_{\text{ref}} \theta_s\right), \tag{8}$$

By using (6)–(8), the average current I_a can be calculated to be

$$\begin{aligned} I_a =& \frac{2}{\pi} \int_{\theta_s}^{\theta_f} i_a(\theta) d\theta \\ =& \frac{1}{\pi\omega L_s} \left[\frac{(\theta_s - \theta_f)}{2\omega L_s} \left(V_p \cos\theta_s + K_v V_{\text{ref}} \theta_s\right) \right. \\ & \left. + V_p \left(\sin\theta_s - \sin\theta_f\right) + \frac{K_v V_{\text{ref}}}{2} \left(\theta_s^2 - \theta_f^2\right) \right]. \end{aligned} \tag{9}$$

Equation (9) can also be rewritten in a simplified form as

$$I_a = \frac{\frac{c_1 V_p}{c_2} - K_v V_{\text{ref}}}{R_{eq}} \tag{10}$$

where

$$\begin{aligned} c_1 =& \frac{(\theta_s - \theta_f) \cos\theta_s + 2\omega L_s \left(\sin\theta_s - \sin\theta_f\right)}{2\pi\omega^2 L_s^2} \\ c_2 =& \frac{(\theta_f - \theta_s) \left[\omega L_s \grave{e}_f + (1 + \omega L_s) \theta_s\right]}{2\pi\omega^2 L_s^2} \\ R_{\text{eq}} =& \frac{1}{c_2}. \end{aligned} \tag{11}$$

Therefore, by using (10) and (11), the equivalent circuits can be concluded as Fig. 3(b) depicts, where the term $I_a R_{\text{eq}}$ indicates the equivalent voltage drop. From this figure, it is also revealed that the circulating current flowing around the overall system is related to the amplitude of the dc capacitor's voltage $K_v V_{\text{ref}}$. In other words, by varying the value of $K_v V_{\text{ref}}$, the circulating current can be controlled easily. At this stage, the testing power S_t drained from the UPS to the burn-in tested system is computed as follows:

$$S_t = \frac{\sqrt{3} \times V_p I_a}{\sqrt{2} = 1.255 \left(c_1 V_p^2 - c_2 K_v V_{\text{ref}}\right).} \tag{12}$$

B. Sinusoidal Utility Current Control

After the control strategy of circulating current is determined, the concern becomes focused on the issue of harmonic compensation. It is expected that the harmonic pollution of the UPS brought to utility ac sources can be better curtailed. As current-controlled inverter technology comes with a faster response, it was adopted in the proposed method [8], [9]. For this design, the conventional harmonic current injection method was initially considered [10]–[12]. However, by applying such a method to the burn-in test system, both signals of UPS input current and tested system output current were required to send to the controller, where one is used to express the needed harmonic components and the other is for the actual output current feedback. In other words, a large number of current transformers must be installed at the corresponding branches for signal-sampling needs. To solve this issue, it was then found that if the utility current can be directly driven to be sinusoidal, then the objective of the harmonic compensation is, indeed, achieved. Based on this idea, the current transformer is thus installed at the utility network side rather than at other branches. With this design plus the assistance of the current regulator, the utility current is, therefore, found to be driven in phase with utility voltage, improving the power factor and increasing the immunity of possible harmonic infiltration to the utility network.

C. Control Block Diagram

For the proposed system, the controller of the grid-connected inverter is composed of two loops. One is the voltage loop responsible for the adjustment of dc capacitor voltage $K_v V_{\text{ref}}$ in order to provide a circulating current control and the other is the current loop designed to offer the switching signals for the harmonic suppression of utility current. These two loops can be well coordinated inside the controller, where the voltage loop is the first loop of the controller whose output signal is then fed to the current loop such that the required gating signals can be generated for semiconductor switches. Fig. 4 depicts this control block diagram. In the diagram, the dc capacitor voltage V_{actual} is seen first compared with the desired value of V_{ref}, where the PI regulator is served to minimize the amount of comparison error. At this step, through the low-pass filter, a reference sinusoidal waveform is also obtained that was sampled by the potential transformer. Then, this reference sinusoidal waveform is multiplied by the PI regulator output in order to drive the resultant waveform in phase with utility voltage, which also ensures the realization of the reference utility current signal. Now, in the subsequent current loop, this reference

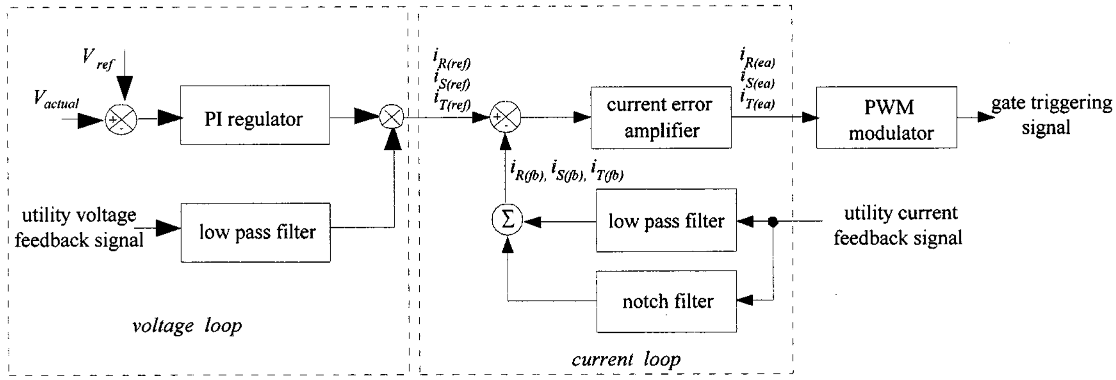

Fig. 4. Control block diagram of the inverter.

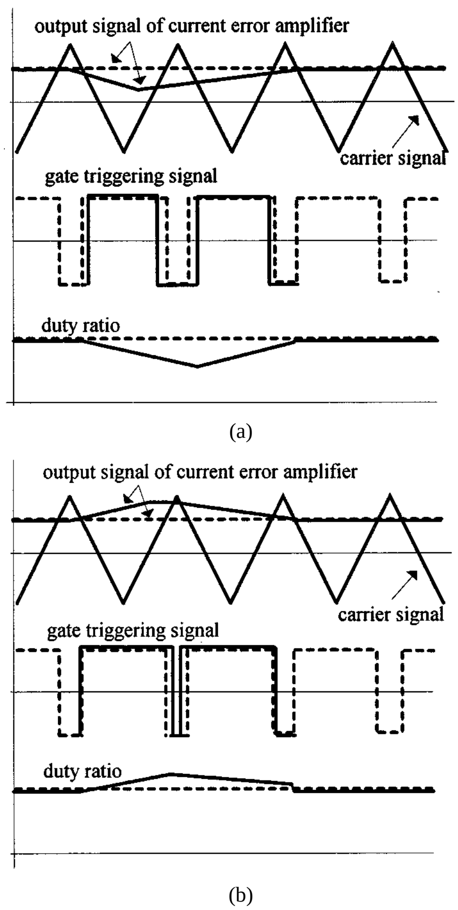

Fig. 5. Triggering signals generation in the controller when undesired noises appear. (a) Spike noise. (b) Dip noise.

utility current signal can be subtracted from the actual utility current ($i_{R(fb)}, i_{S(fb)}, i_{T(fb)}$), where the difference is then delivered to the current error amplifier. The output of the current error amplifier ($i_{R(ea)}, i_{S(ea)}, i_{T(ea)}$) is then transmitted to the PWM modulator such that the required switching signals can be provided for semiconductor switches.

Note that, in Fig. 4, in addition to allowing the current feedback signal to be passed through the low-pass filter, a notch filter of line frequency is also seen added. Fig. 5 explains the purpose of this controller design. As Fig. 5(a) delineates, first suppose that some noises like the spike may appear at the utility current when the system suffers the problem of low current feedback signal in the controller. At this time, the notch filter can sense the noise and generates an inverse signal through negative feedback to decay the magnitude of the output signal of the current error amplifier. Then, by comparing the signal of the amplifier output with carrier signal (triangular waveform), the duty ratio of semiconductor switches is accordingly reduced. This shrinkage of the duty cycle will be useful to restrict the rising rate of the spike. Fig. 5(b) is another case where the dip noise appearing at the utility current is assumed. In the plot of this case, the inverse signal passing through the negative feedback is fed into the error amplifier. For this case, the duty cycles of the switches is accordingly enlarged. Namely, utility current will be pulled up in order to withstand the dip noise disturbance. For the above two cases, the utilization of the notch filter is shown to be beneficial to the improvement of controller performance. However, it must be also noted that, for the application of such a method, the gain of the notch filter should be prudently adjusted in order to meet the design requirement.

IV. Design Considerations

In the proposed burn-in test system, one goal of the controller lies in the harmonic current compensation. However, special attention must be paid to the allowable response of the inverter to the harmonic compensation which is, indeed, limited by the maximum change rate of the inverter output current shown as follows:

$$\frac{di_b}{dt} = \frac{K_v V_{\rm ref} - V_{LL}}{2L_f} \tag{13}$$

where i_b is the output current of the burn-in test system, V_{LL} is the line-to-line voltage of the utility source, and L_f is the output inductance of the inverter. In real-world applications, when the change rate of the UPS's input harmonic current exceeds this value, the output signal of the error amplifier in the controller will become saturated. In such a situation, the inverter fails to accomplish the harmonic compensation. In (13), it also illustrates that a smaller output inductance of the inverter L_f or a higher dc capacitor voltage $K_v V_{\rm ref}$ will help increase the allowable rise rate of the inverter output current.

Fig. 6 reveals the relationships among testing power, dc capacitor voltage, and input inductance, where the test voltages of 120/208 V and 220/380 Vac are individually considered for

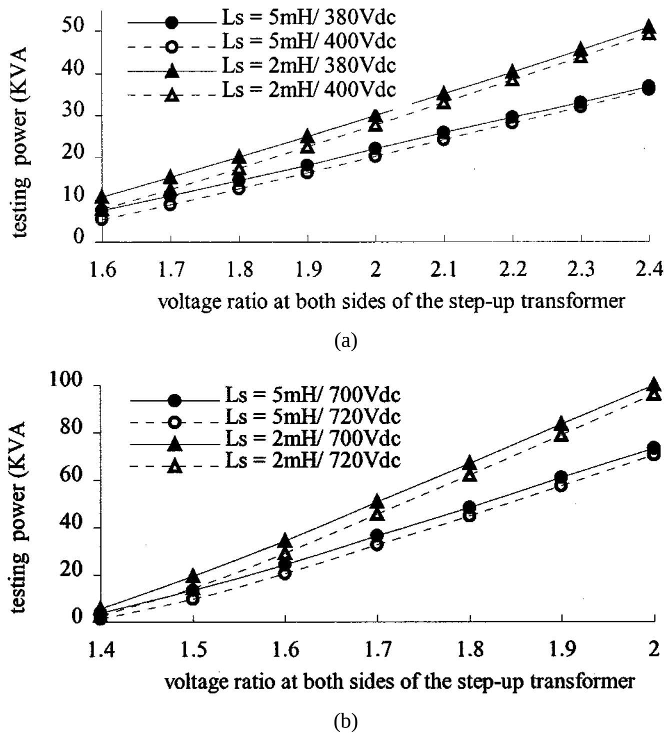

Fig. 6. Relationships between the testing capacity and dc capacitor voltage. (a) For 120/208-Vac system. (b) For 220/380-Vac system.

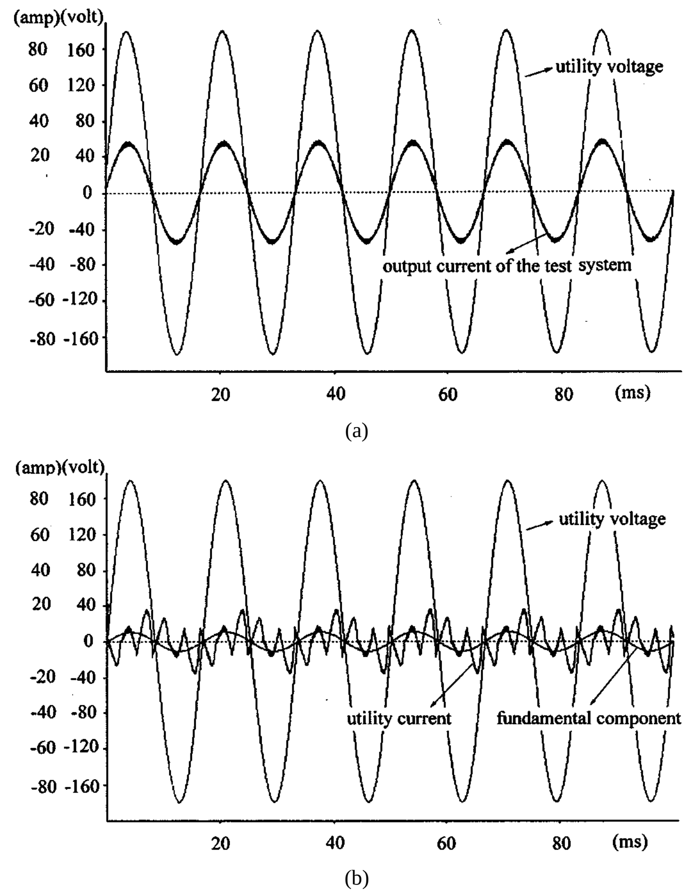

Fig. 7. Simulation results of the conventional burn-in test system. (a) Utility voltage and output current of the test system. (b) Utility voltage and utility current.

the three-phase UPS. In the plot, the testing power S_t in the proposed system is seen related to the amplitude of the dc capacitor voltage. It indicates that under a fixed voltage ratio at both sides of the step-up transformer, a smaller input inductance will result in a larger testing power, while this maximum testing power is found in inverse proportion to the dc capacitor voltage level. Now, as (13) implies that the dc capacitor voltage is also related to the maximum change rate of the inverter output current, the choice of the system parameter becomes a vital task to ensure the expected performance. Conclusively speaking, the parameter selection for the burn-in test system design can be made as follows.

1) Firstly, by taking the harmonic compensation problem into consideration, the output inductance of the inverter L_f and the voltage level of dc capacitor $K_v V_{\text{ref}}$ can be determined.
2) Then, the proper input inductance and voltage ratio at both sides of the step-up transformer are selected such that the testing power can meet the application requirements.

V. Simulation Study and Experimental Results

To validate the proposed method, simulation studies and hardware experiments were both made. The computation software for the simulations was developed based on the ElectroMagnetics Transients Program (EMTP) that runs on a Pentium-III 500-MHz personal computer. In the computation, the transient analysis of control system program (TACS) of EMTP was employed for describing dynamic behaviors of the inverter controller. Fig. 7 shows the simulation results of the conventional burn-in test system, where the utility voltage, output current of the test system, utility current, and its fundamental component are all depicted. As the figure delineates, the magnitude of the utility current is seen to be much lower than that of the output current of the test system. This implies that most of the testing energy can be circulated for the system utilization. However, as shown in the figures, although the waveform of the output current of the test system can be kept sinusoidal and in phase with the utility voltage, the utility current exhibits a serious distortion. This test helps confirm that the harmonic pollution problem may deteriorate the utility power quality.

In order to investigate the feasibility of the proposed system, a hardware prototype has been implemented and tested in the laboratory. The schematic diagram used for the building of this laboratory prototype is shown in Fig. 2, and Table I lists the

TABLE I
MAIN PARAMETERS OF THE PROTOTYPE

Dc bus voltage	380V
Switching frequency	10KHz
Utility voltage	$220V_{LL}$
DC capacitor	2800uF
Filter inductor	3mH
Turn-ratio of step-up transformer	1.35

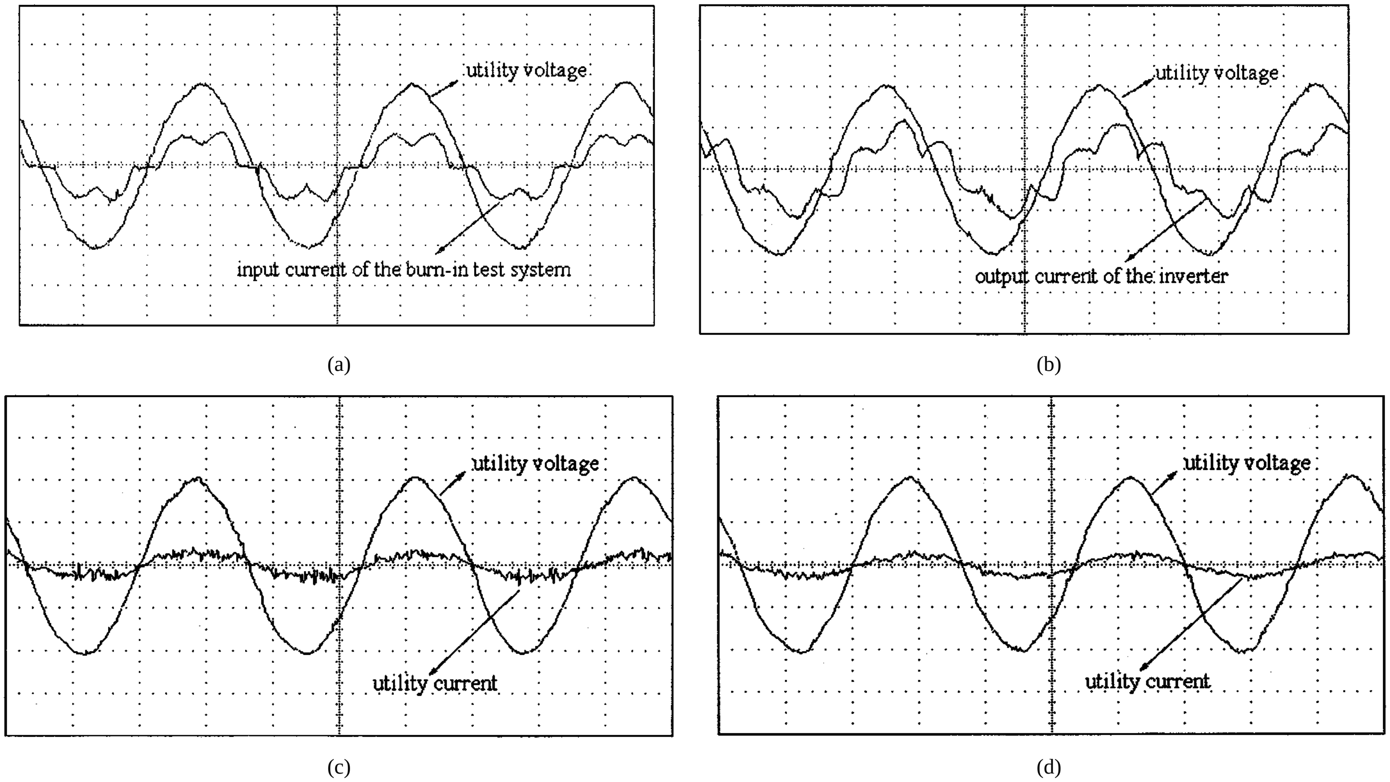

Fig. 8. Experimental results of the proposed burn-in test system. (a) Utility voltage and input current of the burn-in test system. (b) Utility voltage and output current of the inverter. (c) Notch filter is not included in the controller. (d) Notch filter is included in the controller.

related parameters of the proposed method. Two test cases and their results are described as follows.

Case 1: Low Kilovoltampere Testing: In this case, the experiment is conducted through low-kilovoltampere testing, where the input inductance is 5 mH and the test power is 2.7 kVA which is deemed low power from the perspective of a three-phase UPS. Fig. 8 shows the test results. In Fig. 8(a), the input current of the burn-in tested system is seen to present a six-pulse rectified current waveform that means the tested system is operated as a virtual rectified load for the UPS. In Fig. 8(b), the output current of the inverter is also plotted. From this figure, it is seen that, as the inverter is employed to compensate the UPS harmonic current, its output current contains rich harmonics. Fig. 8(c) and 8(d) individually illustrate the utility current waveforms obtained with and without the notch filter. Fig. 8(c) shows that the controller operated without the notch filter may not effectively steer the utility current to be sinusoidal, where a large amount of noise is seen superposed at the current waveform. On the other hand, as shown in Fig. 8(d), with the feedback design of the notch filter implemented in the controller, the noise disturbance is significantly suppressed.

In this test case, the inverter output current is measured at 6.89 A, while the utility current is only 0.63 A. The efficiency of the energy recovery in this test case is computed to be 91.6%, which supports the feasibility of the method. In addition, if the running time of the burn-in test is t_b (hours) and the testing power is S_t (kVA), then the energy saving E_s can be computed as follows:

$$E_s = 0.916 S_t{}^* \cos\theta_{\mathrm{UPS}}{}^* t_b \text{ (kWh)} \tag{14}$$

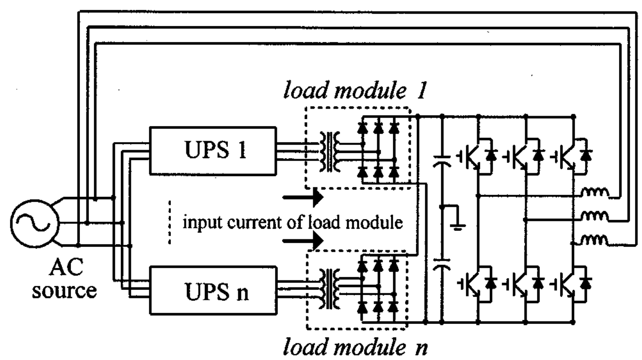

Fig. 9. Parallel operation of the proposed system.

where θ_{UPS} is the input power factor of the tested UPS. In most UPSs manufactured, t_b is commonly set to at least 6 h operated under full load.

Case 2: Parallel Operations: For commercial applications, a large number of new products may need to perform the burn-in test at the same time. In such a scenario, the parallel operation of burn-in test systems is considered. Fig. 9 shows the schematic diagram of the multi-UPS burn-in tests, where the transformer and rectifier are seen included as a load module. In this configuration, because each tested UPS uses an individual load module, it can be independently switched on or off from the burn-in test system.

Fig. 10 illustrates the experimental results obtained when two load modules are simultaneously activated. The total testing power is 4 kVA. Fig. 10(a) draws the input current waveforms of

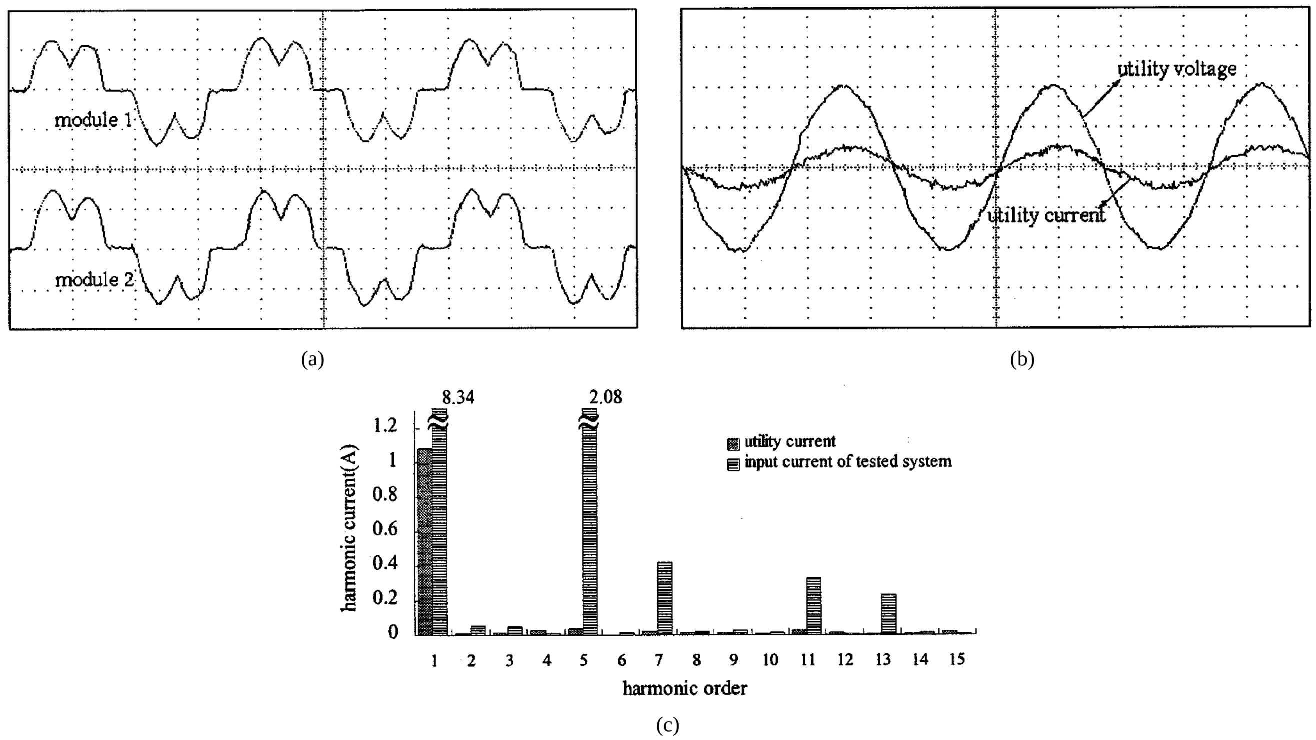

Fig. 10. Experimental results of burn-in test systems that are operated in parallel. (a) Input current of load module. (b) Utility voltage and current. (c) Spectrum of utility current and tested system input current.

individual load modules. Two rectified currents are seen flowing to the inverter from different modules. This means that two UPSs can be tested at the same time. Fig. 10(b) draws the utility voltage and current waveforms and Fig. 10(c) delineates the corresponding spectra. From these figures, the major harmonic components such as the 5th-, 7th-, 11th-, and 13th-order harmonics are seen effectively compensated, which ensures that utility current becomes more sinusoidal. Hence, undesired harmonics and reactive components included in the needed power from the grid were also largely decreased. This implies that the quality of utility voltage at the test side is not affected by the UPS burn-in test, confirming the reliability and practicality of the method.

VI. Conclusions

In this paper, a new approach to a burn-in test for a three-phase UPS has been presented. With the application of this method, the test power can be recycled for reuse such that the experimental cost can be largely reduced. In addition, the proposed method is useful in restricting the degree of harmonic pollution that may affect the utility grid. Electric power quality can also be better ensured. Currently, with the financial support from the utility, this method is being applied for the burn-in test of battery chargers and ac motor drives. At this stage, the reliability of the method is the major concern. Test results will be reported in the future.

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Shyh-Jier Huang (M'95–SM'01) received the Ph.D. degree in electrical engineering from the University of Washington, Seattle, in 1994.

He is with the Department of Electrical Engineering and is the Project Manager in the Computational Intelligence Applied to Power Laboratory, National Cheng Kung University, Tainan, Taiwan, R.O.C. From 1989 to 1991, he was involved in several projects in the Department of Electrical Engineering and Computer Science, University of California, Berkeley. His current areas of interest are energy conversion, power quality, and signal processing applications.

Dr. Huang has received a number of research awards from the National Science Council, Taiwan, R.O.C.

Fu-Sheng Pai received the Bachelor's degree in electrical engineering from Fen-Chia University, Taichung, Taiwan, R.O.C., in 1993. He is currently working toward the Ph.D. degree at National Cheng Kung University, Tainan, Taiwan, R.O.C.

His main areas of interest are power electronics, energy conversion, and industrial electronics applications.